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PRINCIPAL INVESTIGATOR: James H. Stuhmiller
Lucy Bykanova Laurel Ng
Philemon Chan Eugene Niu
Xinglai Dang Paul H. Rigby
Adam Fournier Weixin Shen
Diane W. Long Louise M. Stuhmiller
Zi Lu Brenda J. Tracy
Paul Masiello Jonathan Zhang

CONTRACTING ORGANIZATION: Titan Corporation
San Diego, CA 92121

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James H. Stuhmiller, Lucy Bykanova, Philemon Chan, Xinglai Dang, Adam Fournier, Diane W. Long, Zi Lu, Paul Masiello, Laurel Ng, Eugene Niu, Paul H. Rigby, Weixin Shen, Louise M. Stuhmiller, Brenda J. Tracy, Jonathan Zhang
Email: James.Stuhmiller@L-3com.com

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14. ABSTRACT

This report summarizes the first year of a 5-year program to develop physiologically and biomechanically based mathematical models that will allow the estimation of physical and cognitive performance decrements from blunt trauma and inhalation insult. The progress is captured in this report as brief summaries of individual projects that have lead to a variety of knowledge, software, and hardware products, which in turn point the reader to more comprehensive reports and journal papers. This work provides the products called out in the Military Operational Medicine Research Program (MOMRP) Pulmonary Injury Hazards roadmap. The work supports the on-going, collaborative research between the MOMRP and other military (the US Army Center for Health Promotion and Preventive Medicine, the US Army Research Laboratory, the US Army Natick Soldier Center, the Joint Non-Lethal Weapon Director, and others) and civilian research agencies (the US Environmental Protection Agency, the Department of Justice, National Institute of Justice, National Highway Traffic Safety Administration, and others).

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Blast, Overpressure, Injury, Modeling, Blunt Trauma

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1. Introduction

1.1 Background

The Military Operational Medicine Research Program (MOMRP) of the US Army Medical Research and Materiel Command (USAMRMC) is responsible for the health, protection, and well being of the solider in an extremely wide range of circumstances and stressors. These stressors can arise from environmental, metabolic, materiel and neuropsychiatric causes and can interact in complex ways within the body. It is the responsibility of the MOMRP to conduct research that will anticipate, assess, and prevent the detrimental effects of military operations.

Because the scope of operational medicine is so broad, the interactions are extremely varied, and because materiel changes are so rapid, the need for solutions is usually urgent. On the other hand, these problems usually involve complex interactions of the man and equipment, so the solutions must be grounded in physiology as well as engineering. Both of these components have their own extensive literature and specialties, yet there have been historically little interaction.

The MOMRP has realized this need for rapid, reliable answers to an ever changing suite of stressors and therefore is developing a broad modeling capability that can deal with new problems in the most efficient manner. This long term strategy includes developing general mathematical models of biomechanics and physiological response; capturing and preserving experimental data that validates these models; conducting key biological studies that provides missing data or insight; and unique test equipment that can provide the critical environmental or material data to make the assessments.

This research is conducted within the context of solving current military problems and producing near-term products that help the soldier. This strategy of placing the research within the context and timeframe of real problems has been highly effective in addressing the most important scientific issues and in producing timely and meaningful solutions.

In addition, the MOMRP has formed alliances with other governmental agencies that are facing similar stressors, but perhaps in a different context. For example, MOMRP works with the Department of Transportation National Highway Traffic Safety Administration (NHTSA) on problems of biomechanical injury to the head and thorax. Both MOMRP and NHTSA share concern over vehicular injury, but more importantly both have interest in establishing biomechanically-based injury criteria. Similarly, MOMRP works with the Joint Non-Lethal Weapon Directorate (JNLWD) on injuries throughout the body due to nonpenetrating projectiles. Again, both MOMRP and JNLWD are interested in establishing biomechanically based injury criteria. MOMRP works with the US Army Center for Health Promotion and Preventative Medicine (USACHPPM) to address specific hazards in operational activity and training. MOMRP provides biomechanically based, medically accepted standards for use in Health Hazard Assessments. Other organizations, such as the US Air Force Research Laboratory (USAFRL) and the US Army Research Laboratory (USARL), work with the MOMRP to get guidance or assistance on specific short term problems.

1.1.1 Dynamic Physiological Modeling

The oxygenation of the blood by the lung through respiration is a critical, life-sustaining process. Maintaining the oxygen intake in the respiratory system, transport through the circulatory system, unloading in the tissue capillaries and absorption in the tissues is a key to a healthy and effective war fighter. The disruption of this process can lead to momentary unconsciousness, decrements in physical and cognitive performance, incapacitation, and death. Disruption can be produced by many causes.

Blast and blunt trauma can injury the lung tissue and reduce the ability for oxygen to be diffused across the air-blood barrier. The violence of the impact, transmitted to baroreceptors, can induce cardiac and ventilation responses that interrupt the oxygenation process. These effects have been seen in animal tests as apnea, reduced arterial saturation, and may even be linked to long term CNS deficits.

Inhalation of toxic gases can dramatically affect the oxygenation process. Most toxic gases alter the ventilation rates either through irritant effects in airways, through afferent nerve responses in the upper airways, or through activation of the peripheral and central chemoreceptor. These effects not only alter the amount of oxygen being delivered, but by changing the ventilation rate itself alter the intake of other gases.

Operations at altitude or in reduced oxygen environments directly affect the ability to oxygenate the blood. Modest reductions can be compensated with ventilation increases, but below certain levels the performance and injury effects occur.

Physical exertion places higher demands on oxygen delivery and thereby changes the levels at which the disruptive mechanisms take effect. The body responds to exercise with increased cardiac output and ventilation that, in sub-maximal ranges are able to maintain nearly normal blood chemistry. Of course, the increased ventilation increases the dose of toxic material inhaled. Furthermore, the body's ability to compensate for reduced oxygen levels from toxic inhalation or trauma is reduced when these systems are already at elevated levels.

The current versions of TGAS model the respiration, circulation, and metabolic processes and include models of the ventilation and cardiac output control due to chemoreceptor response. The model has been validated against ventilation changes and incapacitation from exposures to toxic gases, including hydrogen cyanide, carbon monoxide, hydrogen chloride, nitrogen dioxide, carbon dioxide, and low oxygen. Most of the validating data comes from rodent tests, but some are for goats, monkeys, and man. During the remaining portion of the current research effort, the model will be extended to include death as an outcome and to include models for metabolized gases.

1.1.2 ***Blunt Trauma Modeling***

When body armor defeats a bullet or a blast wave hits the body, the blunt impact creates stress waves that propagate through the chest wall and apply mechanical insults to the lung parenchyma. Tissue damage occurs when the resulted stresses exceed the tissue's capability to withstand them. High level blunt threats cause massive tissue damages that severely diminish the oxygenation function of the lungs and can result in total incapacitation and death. Exposures to lower levels of blunt impacts or blasts usually do not result in death or severe injuries. But they could reduce physical and cognitive performances to a degree that may prevent soldiers from mission accomplishment.

Animal and theoretical studies have shown that excessive stress wave leads to undesirable histological morphologic change of lung tissues such as enlargement of alveolar spaces, alveolar rupture, subpleural, intra-alveolar, and perivascular hemorrhages. The ability for oxygen to be diffused across the air-blood barrier is compromised. Air embolism may occur and lead to cardiac dysfunction and immediate death. Accumulations of edema or hemorrhage compromise the normal respiratory functions such as gas transportation in lung and exchange between lung and blood. The interference to normal respiratory functions of regions of a lung ultimately affects the whole lungs and leads to the reduction of oxygen delivered to the brain or muscles. The violence of the impact, transmitted to baroreceptors, can induce cardiac and ventilation responses that interrupt the oxygenation process. These effects have been seen in animal tests as apnea, reduced arterial saturation, and may even be linked to long term CNS deficits.

Ongoing and previous studies have focused on gross correlations between mechanical insults and the possibilities of developing a certain trauma. It has produced mathematical models that are capable of predicting the stress wave propagation inside the lungs and their correlations with severe lung injuries such as pneumothorax, hemothorax, severe lung contusion. However, in order to be able to integrate the biomechanical models with physiological model to predict performance, tissue damages and functional changes, including its location, severity, and the progression, have to be better quantified. This requires a deeper understanding of the mechanisms at the tissue (microscopic) level. The effects of local tissue damage on the functions of regions of lung and whole lung have to be understood, which requires accurate anatomical and functional models of lung at both macroscopic and microscopic levels. And finally the patho-physiological responses of body to the reduced lung functions have to be quantified.

1.2 Hypothesis

Animal studies and the corresponding physiological modeling have shown that, for a wide range of toxic gases, incapacitation is related to a reduction of oxygen delivered to the brain or muscles. Exercise physiology and cognitive studies in humans have established a link between reduced oxygen transport and physical and cognitive performance. If oxygen delivery and absorption is a correlate of both performance decrement and incapacitation, then accurate prediction of oxygen delivery and absorption processes may provide a basis for predicting performance endpoints for a wide range of inhalation and trauma challenges.

The sequence of processes leading to pulmonary injuries and performance decrement can be identified as 1) blunt impact or blast causes stress wave to propagate through chest wall and stress lung parenchyma tissue; 2) over stresses cause tissue damage and consequently change histological morphologic properties and interrupt the normal function of alveoli at local level; 3) the pathological responses of local tissues add to affect the function of regions of lung and ultimately decrease the function of whole lungs; (4) whole body systemic response leads to the decrease in oxygen delivery to brain and muscles and/or cardiac dysfunction and consequently traumatic injuries or performance decrement. If each process is accurately modeled, then the injurious and performance outcomes due to blunt threats can be determined.

1.3 Technical Objectives

At high doses, exposure of war fighters to gases generated in fires or from toxic materials, or exposure to reduced oxygen atmospheres that occur at altitude or in confined spaces, can result in total incapacitation, lung injury, and death. Previous work has produced a mathematical model (TGAS) that is able to capture the physiological response to a wide range of inhaled gases and to correlate internal dose with incapacitation and death. At lower doses, these exposures can produce reduced physical and cognitive performance that can cause the war fighter to be unable to escape danger, defend himself, or make critical mission decisions. Performance decrement can also result from blast and blunt trauma. System and individual vulnerability assessment, safety and protection design, and individual and unit effectiveness evaluations require an accurate assessment of these performance decrements.

The objective of this research effort is to extend the existing mathematical models to predict physical and cognitive performance decrement, validate the model against human and animal test data, release an advanced version of the software (TGAS-PE) that can be used for all inhalation evaluation purposes, and couple the physiological models with the blunt trauma models for tissue and organ injury to provide performance decrement estimations from all pulmonary hazards.

Blunt impact and blast can cause significant lung damages that result in total incapacitation and death or reduced physical and cognitive performance that prevents the war fighter from escaping danger, defending himself, or making critical mission decisions. System and individual vulnerability assessment, safety and protection design, and individual and unit effectiveness evaluations require an accurate assessment of both injuries and performance decrement. The whole pathway from mechanical insults to outcomes, including stress propagation, progression of tissue damage and histological morphologic change due to over stress, degradation of lung functions, and patho-physiology responses, has to be accurately quantified.

The main objectives of this research effort are 1) to develop advanced lung models that include multi-scale mechanical, anatomical, functional, and patho-physiological components to predict the acute trauma and performance decrement due to blunt impacts and blasts; 2) validate the models against animal test data; 3) integrate and release models into an application software that can be used for all blunt pulmonary hazards evaluation purposes; 4) and finally couple the blunt models with the toxic gas models to provide injury and performance decrement assessment from all pulmonary hazards.

1.4 Year 1 Progress

The work has produced 14 products in a wide range of applications. Finite element modeling has been validated against the occurrence of lethality at high level blast when the body is unprotected. These models have been used to develop software that estimates the injury behind personal body armor for both nonpenetrating ballistic impact and blast. A sheep finite element model has been developed to better interpret the results of using animals in blast lethality testing. New versions of the blast injury software, INJURY 8.2, and the toxic gas inhalation hazard software, TGAS 2.0P, have been released through the MOMRP website. The INJURY software has been extended to predict lethality and has been used to assess hazard during pilot ejection from the Joint Strike Fighter. Improvements to the Blast Test Device are aimed at understanding thoracic loading under personal armor. Work to recover and preserve test data from the Blast Test Site continues.

Modeling has been used to understand the effects of blast on the head. New instrument concepts are characterizing head loads under motorcycle helmets during severe impact. The next generation test dummies are being evaluated for biofidelity and software has been developed to assist researchers in accessing and interpreting the dummy instrumentation. Finite element models have been applied to seat belt loading and resultant internal injury.

This year's work produced 10 reports, conference papers, and peer-reviewed journal articles and released two new versions of injury assessment software.

2. Project Summaries

The following brief summaries of individual projects have lead to a variety of knowledge, software, and hardware products, which in turn point the reader to more comprehensive reports and journal papers. This work provides the products called out in the Military Operational Medicine Research Program (MOMRP) Pulmonary Injury Hazards roadmap.

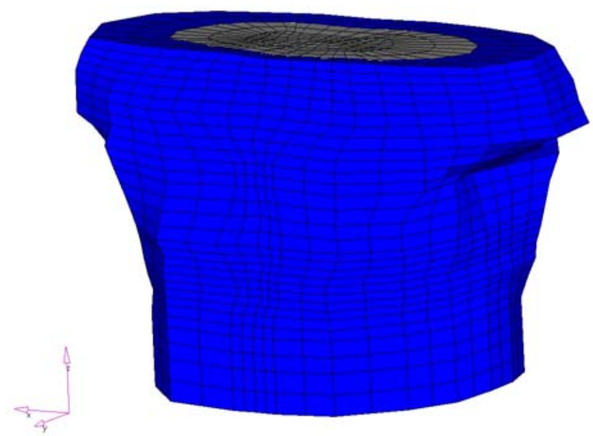
HUMAN FEM VALIDATION AGAINST BLAST DATA (NO ARMOR)

Significance

The human thorax FEM previously developed by L-3/Jaycor has been validated against bare large animal blast test data. The model predicts the human lung response and calculates the normalized work to predict the probability of lethality with validation against large animal data.

Product

--Finite element model of human thorax and normalized work algorithm implemented in LS-DYNA, Paul Masiello (2006).

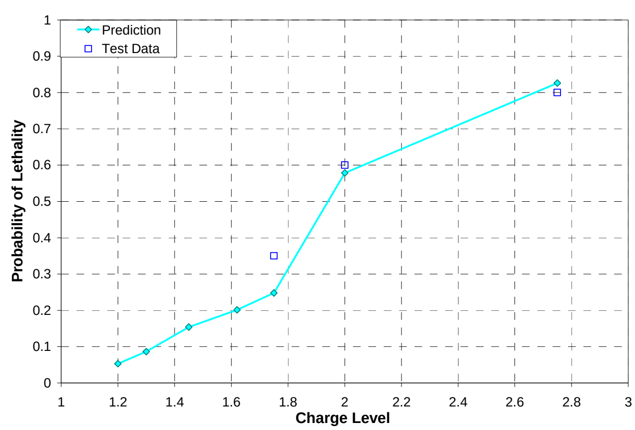


Human FEM schematics

The human thorax finite element model (FEM) previously developed by L-3/Jaycor for blast simulation has been validated using the bare sheep blast test data. BTD data were applied to the four sides of the thorax FEM to simulate the thorax response and compute the normalized work of the lung for lethality prediction. Simulations were performed for the full range of charge levels for a complex (enclosed) condition for the latest tests conducted by Natick Soldier Center.

Since field tests were performed using sheep, the lethality data comparison for the FEM was accomplished with the help of INJURY 8.1. This was easily done because a linear relationship was established between the normalized work calculated by the human FEM and that by INJURY 8.1. In addition, the lethality correlation to normalized work for INJURY 8.1 was previously established. Therefore, the FEM-calculated normalized work could be related to the sheep lethality data through INJURY 8.1. The results show an excellent comparison of the FEM lethality prediction with data.

The model is being used to support the Army ATO for Individual Protection against Novel Blast Threats.



Validation Results

L3 communications

SHEEP FEM DEVELOPMENT

Significance

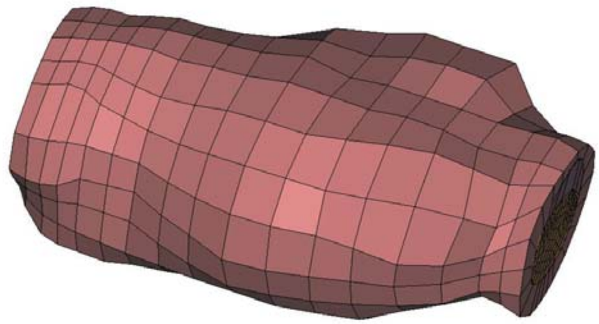
A sheep thorax finite element model has been developed for blast simulation. The model provides a needed tool for understanding of blast injury mechanisms since field tests are conducted using sheep. The model can be coupled with armors for the development of blast protection concepts.

Product

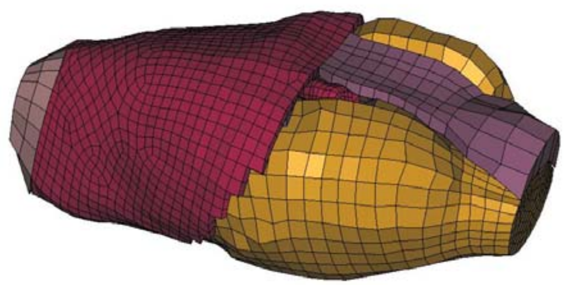
--Sheep finite element model implemented in LS-DYNA, Xinglai Dang (2006).

A sheep finite element model (FEM) has been developed for simulating the sheep response under blast. The sheep FEM includes the skin, bone structures, lungs, heart, liver, spleen, pancreas, kidneys, diaphragm, and the lower abdomen. The skin elements simulate the combination of the outer skin and under skin muscles, and are modeled as solid elements. The bone structures represent the ribcage, spine and neck and are modeled as continuous solid structure to save simulation time. Solid elements are used for all internal organ models. Membrane elements are used for the diaphragm. The head and extremities are excluded. Material properties published in the open literature are used. The parts composing the bone structure is connected together through using shared nodes in the interfaces. The diaphragm hoop edges connect to the ribcage interior surface. The remaining parts are modeled as independent parts. Contact interfaces are defined between all neighboring parts.

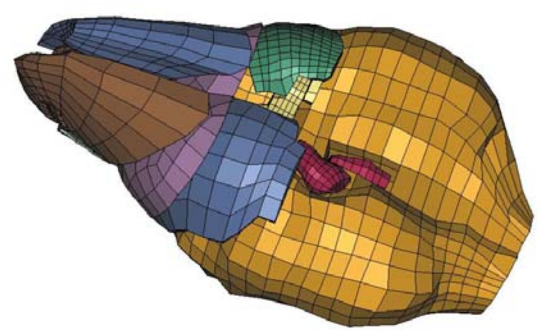
The model fulfills a critical need for direct comparison of modeling results with field data since sheep is used in most of the field tests. The model can be used to study injury patterns for the lung and internal organs for comparison with the extensive set of pathology data collected from the historical BOP test to improve understanding of blast injury mechanisms. Armor models can be coupled to the sheep FEM for the study of blast protection concepts with field data comparison.



Sheep model external view



Sheep model without skin



Sheep model without skin and bone structures

Blast Health Hazard Assessment for Joint Strike Fighter

Significance ⏩

The new Modified Blast Test Device (MBTD) and the HHA software were used for a blast health hazard assessment of the noise generated by the explosive cutting of the canopy during pilot emergency escape for the Joint Strike Fighter (JSF). The results supported the program office in selecting a cutting pattern for the first human flight test.

Product ⏩

--Preliminary Analysis of JSF Noise Test Data using INJURY 8.1, P.C. Chan and Kevin Ho, submitted to JSF and AFRL, October 2006.

MRMC was requested by the Joint Strike Fighter (JSF) program office to conduct a blast health hazard assessment (HHA) for the noise generated by the explosive cutting of the canopy during emergency crew escape. Recent pressure data collected at the dummy chest during ejection tests showed that the blast level generated would exceed the Bowen's lung damage threshold. Since Bowen's Curves were developed for freefield conditions, there were concerns about their applicability to the cockpit condition where complex blast environment would be expected. Recognizing that the MRMC blast health hazard assessment methodology based on the INJURY model and the Blast Test Device has been developed and validated for both freefield and complex conditions, the JSF program office requested L-3/Jaycor to conduct the blast health hazard assessment for the JSF under contract to MRMC with the Air Force Research Laboratory (AFRL) serving as the COTR.

There was additional concern that highly non-uniform pressure pattern could develop on the thorax of the pilot during the explosive cutting of the canopy because of the extensive line-charge layout of the detonation cord on the canopy. At the time of the study, the optimum detonation cord layout pattern was still being developed to provide effective jettison of the canopy without producing excessive blast level. Therefore, it was requested that L-3/Jaycor would use the newly developed Modified Blast Test Device (MBTD) to collect pressure data. The MBTD was designed to be capable of using up to 36 sensors to map out the pressure contour around the entire thorax. In addition, the on-board data acquisition system developed for MRMC was used for data collection that greatly eliminated complicated cabling.

The first part of the test study was conducted at Pacific Scientific, California, USA using a cockpit mock up to evaluate the noise level generated by various explosive cutting patterns. The test data provided guidance for down selecting a cutting pattern that was considered by the crew escape experts to be able to jettison the canopy effectively away from the pilot during ejection.

The second part of the test study was to measure the noise level in a JSF cockpit for the down selected detonation cord layout design at the Martin-Baker facility in Northern Ireland, UK. Data were collected successively and analyzed. Health hazard assessment indicates a RAC=3 condition for the noise level inside the cockpit for the test conducted. A data report was submitted to JSFL/AFRL. Results were used by the JSF program office as part of the crew escape data for the qualification of the first human flight test.

Data analysis also showed the various detonation designs produced different pressure contours around the thorax. The blast environment inside the cockpit was indeed fairly complex, far from a free blast condition. It was recognized that more tests should be conducted to quantify the noise hazard to support the design of the detonation cord layout.

Cited References:

Masiello, P. (2006) "BOP-HHA Version 2.0 User's Guide," L-3/Jaycor.

"Health Hazard Assessment Program in Support of the Army Materiel Acquisition Decision Process," Army Regulation 40-10, October 1991.

MBTD and on-board data acquisition system.

Set up of MBTD in JSF Cockpit

INJURY 8.2 LETHALITY CORRELATION

Significance

A blast lethality correlation with normalized work was developed using the historical MRMC BOP data and INJURY 8.2. The correlation agrees with the latest data collected from novel blasts.

Product

--Blast Lethality Correlation using Normalized Work, P. C. Chan and Paul Masiello (2006). Proceedings of Military Applications of Blast Symposium (MABS), Calgary, Canada, 2006.

A blast lethality correlation based on the normalized work done on the lungs has been developed with normalized work calculated using INJURY 8.2. The dataset utilized is taken from the complex wave blast tests conducted under the US Army Blast Overpressure Project (BOP). The BOP tests included detailed pathology data for blast injury, with a small number of test subjects having died as a result of blast exposure. Consequently, the BOP tests produced a viable set of blast lethality data. INJURY 8.2 was used because the latest non-linear equation of state for the lung material has been implemented, which is important for strong blast conditions that are expected to result in more lethality. A logistic correlation between lethality and the normalized work calculated by INJURY 8.2 has been established. The correlation has good statistical significance, a reasonably tight 95% confidence band, and agrees well with the binned-BOP data.

The normalized work-lethality correlation provides a more generalized method for predicting lethality due to blast including complex wave environments. In contrast, the historical Bowen curves for lethality are based on free-field waveforms, where a well defined pressure peak and A-duration are required. A lethality correlation based on normalized work done on the lungs suggests that lung injury plays a major role in survival, while it is recognized that other factors might also be of importance.

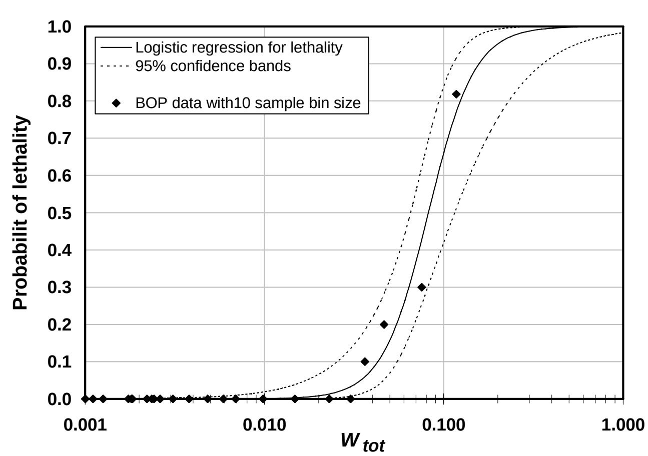
Some limitations of the present work are noted. The test programs from which data were extracted to develop the blast lethality correlation were not originally designed to establish limits for lethality. Rather, these tests were undertaken to study tolerance limits for injury to lungs, trachea, and other internal organs. As a consequence, the data include a relatively small number of fatalities, 15 out of 561 samples. It is also noted that the time of death is not uniform, ranging from 1 to 180 min. Despite this limitation in the number of positive outcomes for fatality, the lethality correlation established shows strong statistical significance, and is in good agreement with the binned data.

The established model for predicting the likelihood of death due to air blast includes only a single risk factor for lethality, the total normalized work done on the lungs by chest wall motion due to blast. The work done on the lungs, however, is normalized by the subject mass, and the mass is also used to scale the material properties of the thorax. Therefore, mass is accounted for in normalized work calculations. It is recognized that other risk factors, such as injuries to solid organs and physiological data, could play a role leading to the full understanding of the mechanism of lethality due to blast. The mechanism to lethality due to blast is still not fully established.

Cited References:

Stuhmiller, J. H. et al. (1996) "A Model of Blast Overpressure Injury to the Lung," *J. Biomechanics*, Vol. 29, No. 2, pp. 227-234.

INJURY 8.2 at http://www.momrp.org/index.htm



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communications

Blast Protection Concepts using Human FEM Coupled with Armor

Significance

The human thorax finite element model has been coupled with armor models for blast simulations and the results have provided guidance for the development of blast protection concepts.

Product

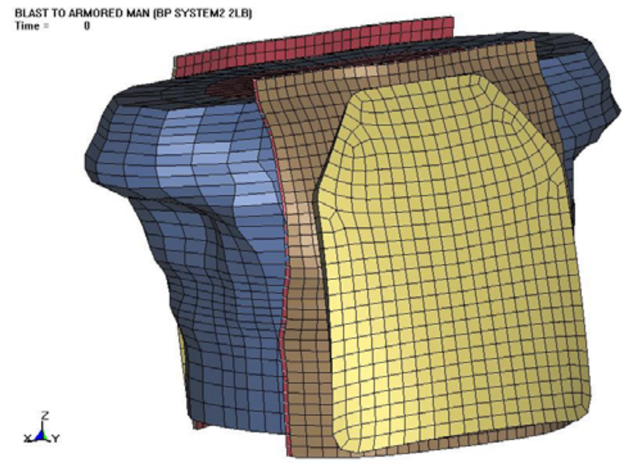
--Human thorax FEM model coupled with armor models and simulation results, Xinglai Dang (2006).

A series of finite element model (FEM) simulations has been performed to evaluate the integrated armor protection concepts against blast. The human thorax FEM was first validated against bare animal test data. Finite element models were constructed for various armors and coupled with the human thorax FEM. Simulations were performed using BTD data as load input representing a range of complex blast conditions.

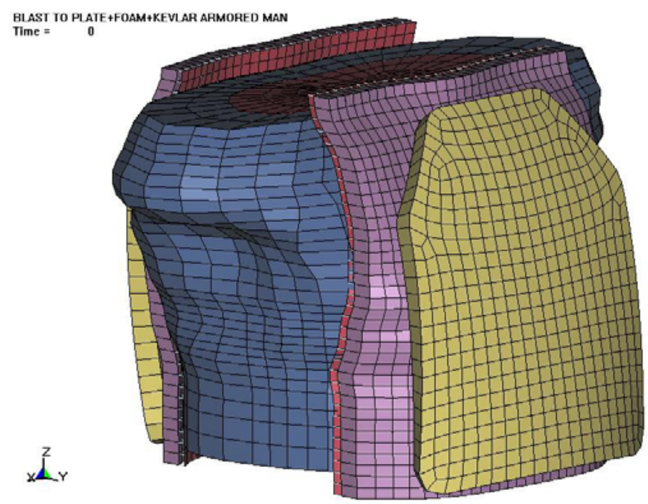
Four concepts were evaluated with comparison against the unprotected (bare) condition. The use of a basic ballistic plate on top of soft Kevlar can reduce the blast lethality by about 20-30%. The addition of foam between the plate and Kevlar provides no additional benefit. In place of the foam, if the mass areal density of the plate is doubled, blast lethality can be reduced by 60-75% when compared to the unprotected condition. The best concept is the body-fitted thin and lightweight unibody concept, Kaijia.0. Compared to the bare condition, the Kaijia.0 concept reduces the lethality by 80-90%. In addition, the Kaijia.0 concept only weighs about 20-30% of a baseline armor.

Lethality Reduction Compared to Unprotected Condition.

Protection concept	*Lethality reduction*
Plate on top of Kevlar	*20-30%*
Plate on top of foam and Kevlar	*20-30%*
Plate with double weight on Kevlar	*60-75%*
Lightweight unibody Kaijia.0	*80-90%*

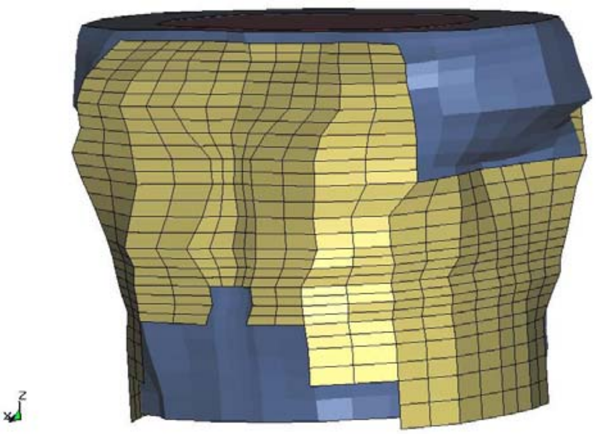


Human FEM with plate and Kevlar

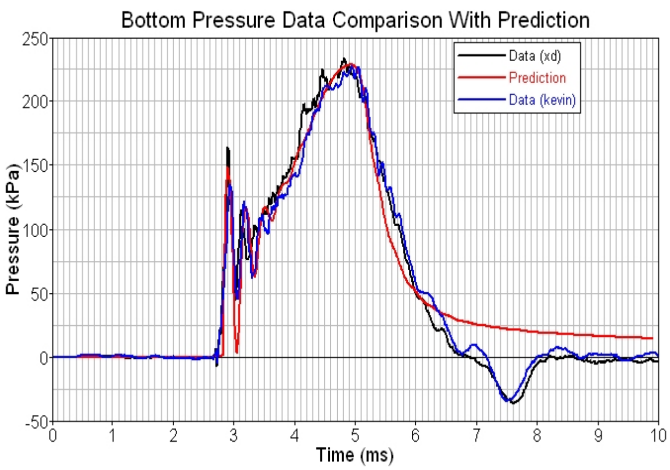


Human FEM with plate, foam and Kevlar

communications



Kaijia.0: Lightweight unibody concept



Plate, foam and Kevlar model shock tube validation results

BEHIND ARMOR BLUNT TRAUMA ASSESSMENT PROGRAM (BABTAP)

Significance

- Web-based user friendly interface
- Three-tie layered architecture: Client (user application) domain, integrated models domain and data management
- Report generation by select-click procedure
- Transparent functions for users and burying inside all complicated research works in background
- Extended collection of related researches and literatures
- Summary/detail report documentation

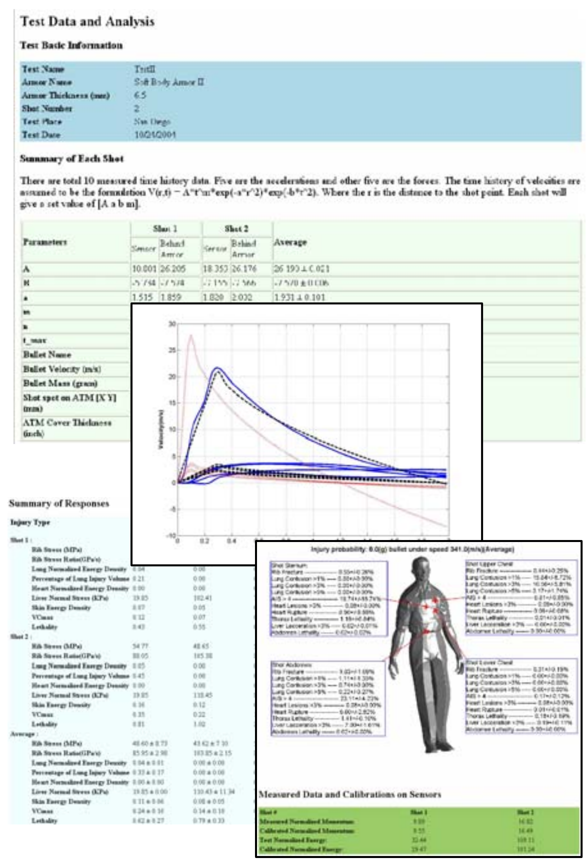
Product

--Body Armor Blunt Trauma Assessment, Part IV: Biomechanically-based Thoracic and Abdominal Injury Correlation, Yuqing Niu, Weixin Shen and Adam Fournier, Final Report J3150.01-06-310, Nov. 2006.

--Behind Armor Blunt Trauma Assessment Program, Web Application, Yuqing Niu, Weixin Shen, Jonathan Zhang.

When body armor defeats an impacting bullet by expanding and deforming, there is a transfer in kinetic energy from the body. This energy transfer creates blunt trauma to the underlying tissues by disrupting and damaging them. In this application, after the live fire test data imported, the behind armor loading estimation and reconstruction are conducted at first. A mathematical formulation is used to descript the back face velocity distribution over time and space and represented by several parameters. In the database of the application, there is a response lookup table from advanced finite element models. It connects the behind armor loading parameters and the human body responses, such as rib maximum normal stress, normalized lung and heart energy density, liver normal stress, skin energy density and some other global values, such as VCmax and Lethality. The data in this table are come from simulations of live fire tests and other virtual hundreds of ballistic cases. The biomechanically-based injury correlations are also included in this program. The blunt trauma injury probabilities and severities are obtained from the injury correlations and body responses. The report gives the summary injury results and detailed test data, reconstruction of loadings, body responses and injury probabilities of each shot.

In addition the injury assessment function, the program also provides the document archive capability and stores the library of armor, bullet and launchers for user to save their reports and manage their data. The literature database gives the ability for user to access related research works.



Behind Armor Blunt Trauma Assessment Program: Loading estimation and reconstruction, responses and injury summary.

The main steps using the program

- Conduct live fire test on ATM
- Input the test information (armor, bullet)
- Loading time history into the software in the client computer
- Run BABTAP analysis to give the report
- Report archived for future analysis
- Armor, bullet and weapon archived in libraries

Cited References:

Shen, W., Niu, Y., and Stuhmiller, J.H. (2005) "Biomechanically Based Correlations for High-speed Impact Induced Rib Fractures, Journal of Trauma 58(3), 538-545.

Shen,W., Niu,Y., Mattrey,R., Fournier,A., Corbeil,J., Yoko,K., and Stuhmiller,J.H. (2006) Development and validation of Subject-specific Finite Element Models for Blunt Trauma Study. Journal of Biomechanical Engineering, Accepted

Niu, Y., Shen, W., and Stuhmiller, J.H. (2006) Finite Element Models of Rib as a Beam Inhomogeneous Structure under High-speed Impacts. Medical Engineering & Physics, Accepted

BEHIND ARMOR CHARACTERIZATION

Significance

Current standard for BA signature that simply measures peak deformation in clay test is significant but insufficient to assess injury. Test and simulation results are indicating that adding additional dynamic measurements, especially the peak BA velocity and the time of reaching the peak, will greatly improve the assessment

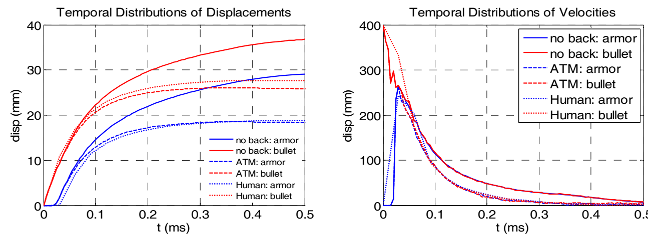
Product

--Body Armor Blunt Trauma Assessment, Part V: Characterization of Behind Armor Signatures and Blunt Injury Assessment with ATM, Lucy Bykanova, Eugene Niu, Adam Fournier, and Weixin Shen, Final Report J3150.01-06-311, Nov. 2006.

Anthropomorphic Testing Modula (ATM) capable to withstand a significant number of ballistics impacts was developed as a surrogate device to characterize bullet-armor-body interaction. Total of 5 equally spaced accelerometer and FlexiForce sensor combination units are embedded inside the sensor block to measure impact force, ATM motion, and their distributions.

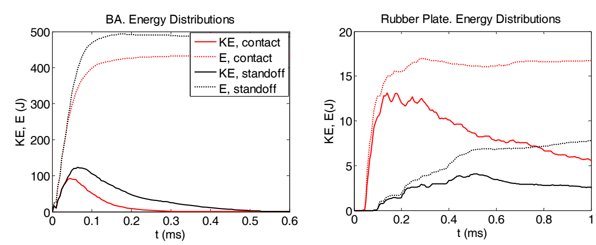
Advanced numerical modeling of bullet-armor-target interaction was applied for reconstructing impact signatures. Numerical models were tested and validated against a significant number of armor systems. FE modeling of Bullet-Armor-Target interaction provides comparative tools for determining responses to ballistic impact and has a potential to evaluate and improve body armor design and efficacy, determine human body injury and assist with injury prevention.

Character of bullet-armor interaction depends on backing material. Presence of backing material affects armor responses. ATM and human body produce the same effects on bullet-armor-target interaction and result in the same BA signatures. This conclusion is confirmed by FE modeling.



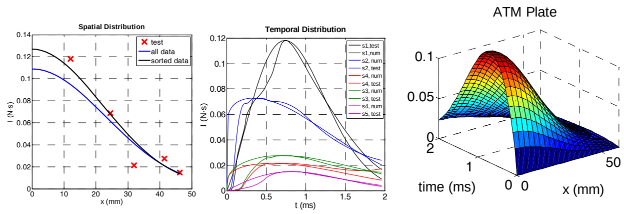
Effects of backing material on armor responses

FE simulations revealed the parameter that makes noticeable differences in BA and ATM responses. This parameter is standoff distance between BA and target. Standoff between body armor and ATM or other target provides with extra time in bullet-armor interaction that involves extra BA mass in process and reduces effective velocity and energy of the BBA impact.



Effects of standoff on armor and ATM plate energy distributions

Detailed analysis and systematization of results for live fire tests allows observation some regularity in sensor readings. Mathematical method can be developed to fit the test measurements and determine the impact signatures for specific armor systems. The temporal and spatial distributions of velocity, impulse, and energy are represented by simple mathematical functions. Shape functions can be extrapolated toward the surface based on analysis of tests results conducted with variation of rubber cover thickness and in combination with FE analysis.



Empirical approach for BBA signatures

Live fire tests using ATM were conducted to determine BA signatures from the measurements and to compare the results of these measurements with the results from laboratory clay test and numerical modeling.

Comprehensive analysis of BBA signatures for wide range of parameter variations was performed. Based on the simulations, an easy modification of the body armor was proposed which may result in significant reduction of blunt trauma probability. Validation of the proposed redesign was confirmed by results of live fire tests.

TGAS 2.0P

Significance

In a fire, in addition to the fire gases that are released, many volatile gases are present that can also threaten life and survivability. The TGAS 2.0P software extends previous software versions to compute the deleterious effects of these other volatile gases. One important class of gases includes the fire suppressant substances, such as Halon. The formulation is built upon physiologically based pharmacokinetic modeling, to which more gases can be added in a systematic way.

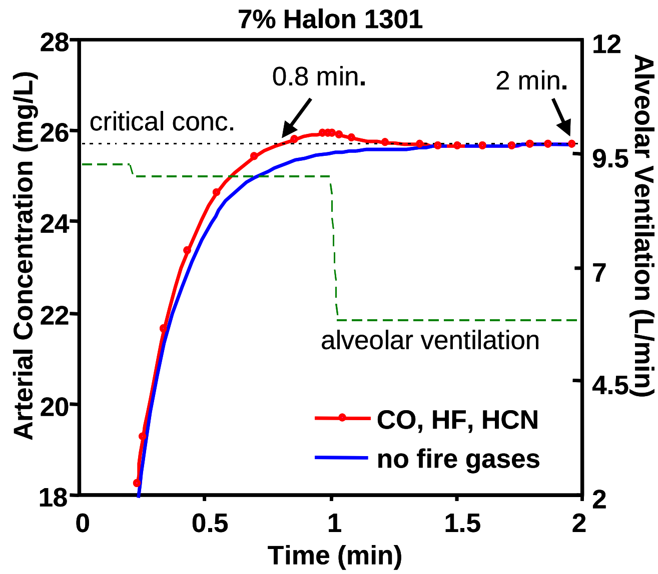
Product

--TGAS 2.0P Model, Laurel Ng (2006).

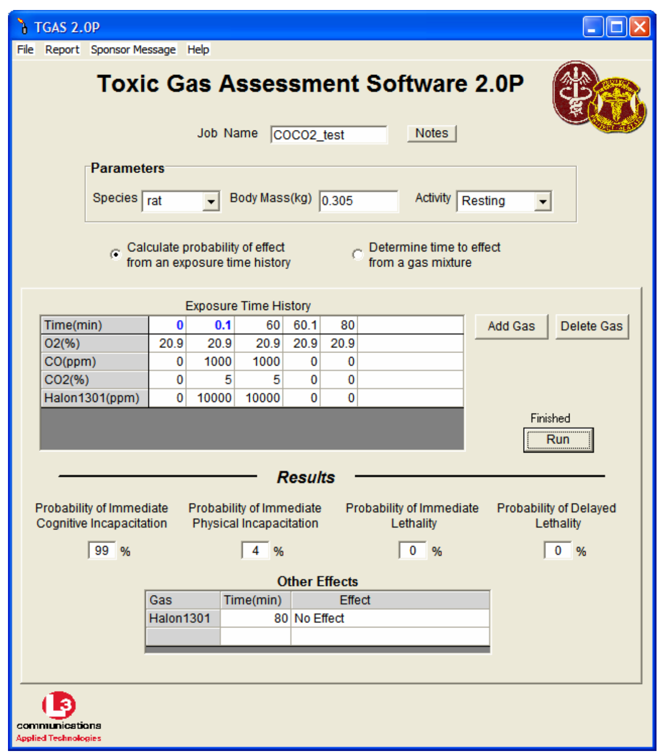
--Incorporation of Acute Dynamic Ventilation Changes into a Standardized Physiologically Based Pharmacokinetic Model, L.J. Ng, J.H. Stuhmiller, and L.M. Stuhmiller, Inhal. Toxicol., 19(3):1-17, 2007.

The PBPK model described elsewhere is combined with the TGAS 2.0 model for fire gas response and outcomes. The combined model accounts for all sources of transient ventilation change: exertion, chemical stimulation, species, and body mass; and relates all outcomes to body-mass normalized internal doses.

The model allows the user to input species, body mass, and an acute, transient exposure profile for up to 29 different gases. The software computes the probability of incapacitation, lethality, or other deleterious effects, when a transient exposure is given, or it computes the time to an endpoint, when a gas mixture is given.



Internal dose comparison plot



TGAS 2.0P input screen

GENERALIZED SKULL FRACTURE CRITERION

Significance

This work has developed a generalized linear skull fracture criterion, the skull fracture correlate, SFC, applicable to impacts by flat targets on the skull in any angle. It is shown that SFC is a biofidelic risk factor for both frontal and lateral impact induced skull fracture.

Product

Chan, P.C., Lu, Zi, Rigby, Paul, et al. (2007) "Development Of Generalized Linear Skull Fracture Criterion," Accepted for presentation at NHTSA 2007 ESV conference, June 2007.

A generalized Skull Fracture Correlate (SFC) for frontal and lateral impact-induced linear skull fracture has been developed. To use SFC, impact tests are performed using the Hybrid III headform. SFC is then calculated as the averaged headform acceleration over the HIC time interval, and the probability of fracture, P, is predicted as

$$\ln\left(\frac{P}{1-P}\right) = 6.39 * \ln(SFC) - 32.53$$

For 15% or less probability of skull fracture the threshold is SFC < 124 g, with a 95% confidence band of 96 < SFC < 144 g.

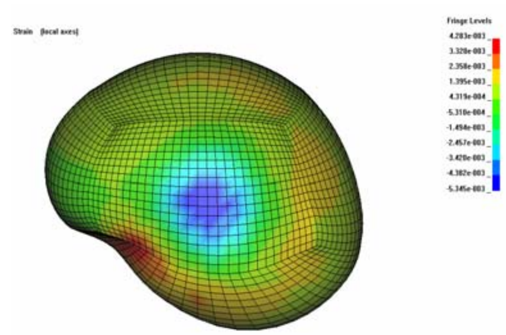
SFC has been validated against an extensive post mortem human specimen dataset consisting of historical data from Hodgson and Thomas (1971 and 1973) and new data obtained by Medical College of Wisconsin. Hybrid III headform tests were performed for each specimen drop to calculate SFC. An anthropomorphic finite element model (Vander Vorst et al, 2004) was used to calculate the skull strain for each drop test. Using logistic correlation, it was found that the calculated peak skull strain, SFC and the fracture data of the head correlate well with each other with good confidence bands. The biomechanical basis of SFC is validated by its good correlation with skull strain.

Cited References:

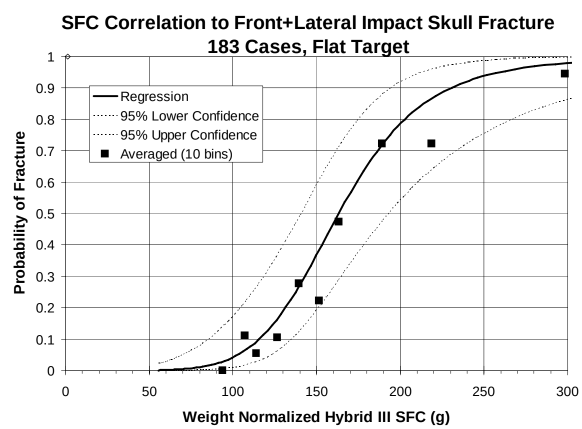
Hodgson, V.R. and Thomas, L.M. 1971. "Breaking Strength of the Skull vs. Impact Surface Curvature," DOT HS-800 583, Contract No. FH-11-7609, Final Report.

Hodgson, Voigt R. and Thomas, L. Murray. 1973. "Breaking Strength of the Human Skull vs. Impact Surface Curvature," Report DOT HS-801002, National Technical Information Service, Springfield, Virginia.

A New Biomechanically-based Criterion for Lateral Skull Fracture, Vander Vorst, M.,P. Chan, et al., Annual Proc Assoc Adv Automotive Med 48: 181-95, 2004.



Skull strain calculated by finite element model.



SFC correlation with fracture data

BIOFIDELITY OF MOTORCYCLE HELMET CRITERIA

Significance

A method for measuring the contact force on a helmeted headform during a FMVSS 218 impact attenuation test was developed. This provided load data input for finite element model simulation of skull deformation without the need for modeling the helmet to evaluate the biofidelity of FMVSS 218.

Product

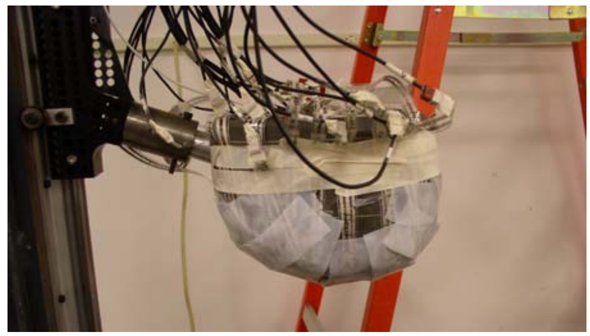
--Measurement of Under-Helmet Force Distribution on FMVSS 218 Headform, P.H. Rigby, P.C Chan, and Z. Lu, Proceedings of the Thirty-Forth International Workshop on Injury Biomechanics Research, 2006.

The objective of this work is to evaluate the biofidelity of the current Federal Motor Vehicle Safety Standard (FMVSS) 218 for motorcycle helmets using the L-3/Jaycor anthropomorphic finite element model (FEM) of the head that has been validated against skull fracture data (Vander Vorst et al, 2004). FMVSS 218 is a generalized safety standard based on acceleration peaks and dwell times. However, the biomechanical basis of FMVSS 218 is not known.

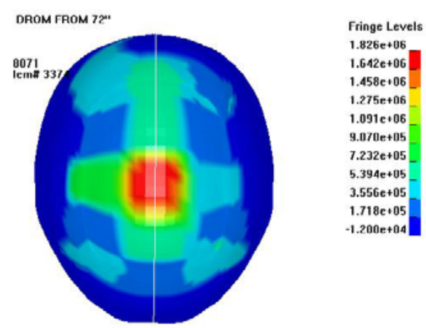
Instrumentation has been developed to measure the pressure distribution on the FMVSS 218 headform using an array of Tekscan's FlexiForce pressure sensors for helmet drop tests. A technique has been developed to eliminate the shear error seen by FlexiForce sensors, giving an accurate pressure-history contour over the headform. Using the headform pressure data as input, the L-3 anthropomorphic FEM was used to calculate the peak skull strain for each helmeted drop test. The methodology has been validated with the FEM-calculated head acceleration showing excellent agreement with the headform acceleration data. An extensive test series is being completed to collect headform pressure data for FEM simulations.

Cited Reference

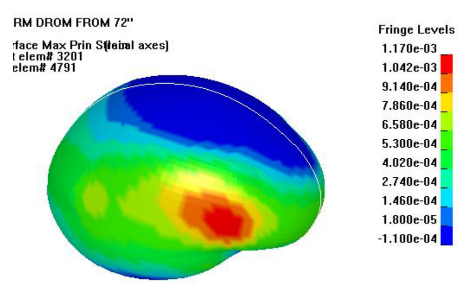
Vander Vorst, M, Chan, P, et al., (2004). "A New Biomechanically-based Criterion for Lateral Skull Fracture," Annual Proc Assoc Adv Automotive Med, 48.



Fully instrumented headform



Pressure distribution on head under helmet measured using FlexiForce Sensors



Skull strain computed using anthropomorphic FEM with FlexiForce data as input.

communications

EFFECT OF BLAST OVERPRESSURE ON THE HUMAN HEAD

Significance

A study of the effect of blast overpressure on a closed head has been performed using finite element model simulations. The results show that head acceleration plays a dominant role in determining the intracranial pressure, while the brain motion and skull deformation add significant complexity to the brain pressure. However, the effects of eye openings and foramen magnum on brain pressure are insignificant.

Product

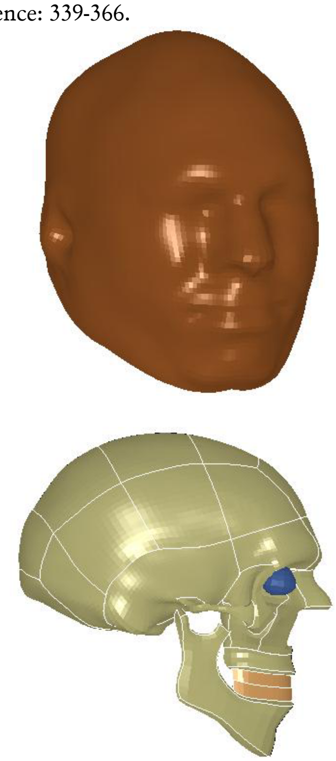
--A Study of Blast Overpressure Effects on Human Head using Finite Element Model Simulation, P.H. Rigby and P.C. Chan, L-3/Jaycor Report J0287-07-319.

A study of the head/brain response to blast overpressure was performed using finite element model simulations. The model of a human head was constructed using CT scans taken from the Visual Human Project. The model consisted of the skin, skull, and brain weighing a total of ten pounds. The skin and brain are homogenous materials. The skull is separated into three distinct layers; the inner table, diploe, and outer table. The skull model includes all facial and jaw bones. The head model is made of over 98,000 block elements. Material properties were taken from previous finite element head impact studies. The head model was first validated against cadaver head impact and intracranial pressure data taken by Nahum et al. (Nahum and Ward 1977). The blast wave was modeled as a Friedlander wave with a peak pressure of 800 kPa and duration of 1 msec, which will produce low probability of trace to slight blast lung injury. The blast wave was applied to the forehead.

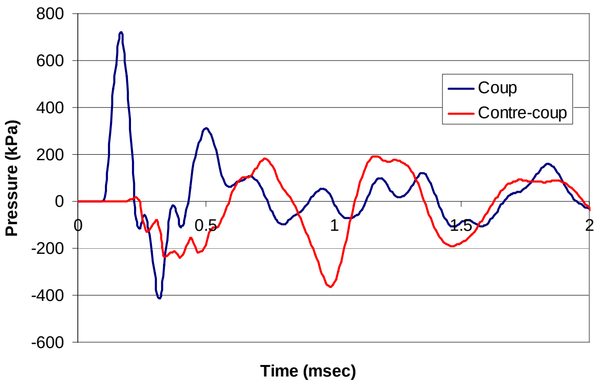
The blast wave produced a peak head acceleration of 340 g., which also resulted in a strong coup-contrecoup pressure gradient seen in the brain analogous to a hydrostatic effect. The maximum coup pressure was 719 kPa with a contrecoup pressure of -227 kPa. However, the coup and contrecoup pressures do not occur simultaneously with the contrecoup pressure lagging the coup pressure by 0.1 msec as a result of the brain motion and skull deformation. Skull deformation and brain motion also caused significant pressure oscillations. Parametric simulations were performed showing the openings in the eyes and foramen magnum had minimal effects on the brain pressure response, confirming that acceleration was the main cause of brain pressure response. Currently there are no validated blast injury criteria for the head and brain although common closed head traumatic brain injury (TBI) criteria are used by some researchers.

Cited Reference

Nahum, A. M. and C. C. Ward (1977). "Intracranial pressure dynamics during head impact." 21st STAPP Car Crash Conference: 339-366.



Head FEM based Visible Man Project



Simulated intracranial pressure from a 800 kPa-1 msec Friedlander Blast on the forehead

THOR GUI

Significance

A user-friendly Windows-based graphical user interface (GUI) has been developed to support the use of the THOR dummy. The GUI enables the users to perform on-screen verification of the instrumentation set up information, the processing and display of the test data, and the checking of potential test set up errors with warnings and provisions for on-screen correction given.

Product

THOR GUI software, Zi Lu and Slava Nisman (2006).

The vendor-supplied THORTEST program that processes the THOR dummy data was written in a way that it requires a highly experienced user to avoid making errors. It has a primitive software interface and relies on two input files that need to be prepared very carefully depending on the input data formats and data collection procedures. These procedures, if not implemented carefully, could easily cause data processing errors. Based on user feedback regarding data processing using THORTEST, at least three shortcomings are identified: (1) for data collection, if a potentiometer is zeroed out, the initial angle or offset must be measured manually every time before a new test is conducted, and that is prone to oversight or error, (2) the data post-processing involves several steps controlled by text-based batch input files that can be confusing, especially for new users, and (3) there is no immediate data display for the processed data.

To support the fielding of the THOR dummy, a user-friendly Windows-based GUI has been developed to process all the data collected by THOR. The THOR GUI runs on top of the THORTEST program and provides an on-screen graphical interface. The GUI shows all instrumentation and dummy configuration parameters, checks zeroing conditions for potentiometers, directs THORTEST to process all input data, displays the results, and stores the output data in user-specified filenames.

The Beta-version of the GUI was released in early 2006. After the release, many comments, suggested refinements and requests for new capabilities from users have been received. A refined version of the GUI will be released in early 2007. The new version will have the following advanced capabilities:

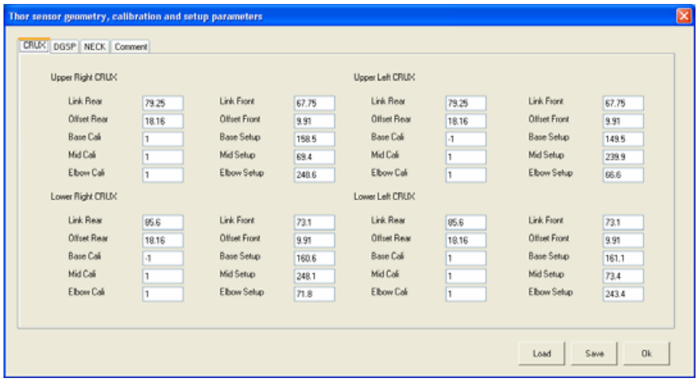
1. Full-proof checking of potentiometer zeroing errors
2. Data display enhancement
3. Flexible data input/output and file management

Cited References:

Haffner, M., Eppinger, R., Rangarajan, N., Shams, T., Artis, M., and Deach, D., (2001) "Foundations and Elements of the NHTSA THOR Alpha ATD Design," Paper #458, 17th International Technical Conference on the Enhanced Safety of Vehicles, HS 809 220 (U.S. DOT, 2001).

User Manual,"THOR Instrumentation Data Processing Program," November 2001, GESAC-01-06.

Instrumentation parameters window



Data display window

communications

THOR-NT Evaluation Test

Significance

The performance of the new THOR-NT dummy was evaluated using different types of airbags. It was confirmed that the THOR-NT dummy is able to differentiate the muscle load from the occipital condyle (OC) load as intended by its head/neck design.

Product

--OOP Airbag Tests using the THOR-NT, Zi Lu and Philemon Chan (2007) Accepted for presentation at NHTSA 2007 ESV conference, June 2007.

An experimental evaluation of the 50TH THOR-NT dummy was performed using five late model driver airbags. Tests were performed with the dummy placed at ISO-1 (chin on bag) out-of-position (OOP). Matching tests were performed for the Hybrid III dummy for comparison. Two repeat tests were performed for each airbag module with the original steering wheel. The Airbag Test Simulator (ATS) was used as the test platform providing tight control of dummy position. Airbag tests were previously performed using the ATS pneumatic system for bag inflation. This latest test study was performed using fleet airbag modules provided by TAKATA. Work was performed to support the development and evaluation of the THOR-NT dummy.

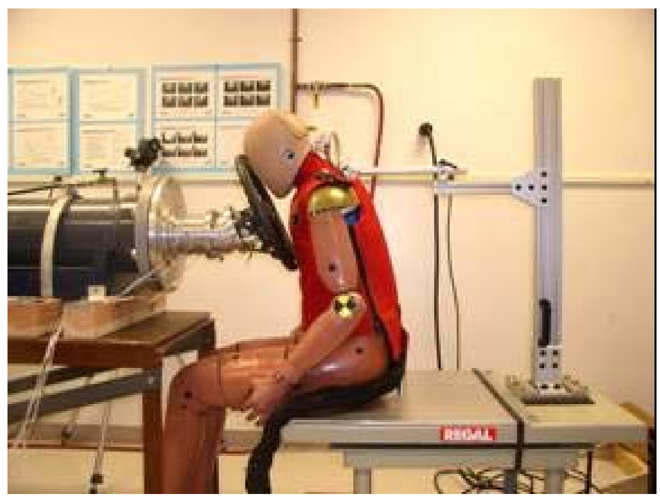
Data show THOR-NT is able to distinguish the neck muscle load from the spinal load. The neck moment measured at the occipital condyle was lower than the cross-sectional moment. In addition, THOR-NT neck tension was mostly measured by the occipital condyle consistent with the expectation that neck tension should mainly be borne by the ligamentous spine, with very little load borne by musculature. The total cross-sectional load includes the muscle effects but it is understood that neck injury should be measured by the spinal loads. The THOR-NT head/neck design is able to distinguish these two load paths.

Compared to Hybrid III, data show the THOR-NT is much less likely to go into hyperextension. Hyperextension is known to be a shortcoming of the Hybrid III neck design. For the airbags tested, THOR-NT measured much smaller neck moments than Hybrid III, and THOR-NT can stay in flexion considerably. Overall data suggest that THOR-NT is more biofidelic than Hybrid III, but injury criteria are still not developed for THOR-NT.

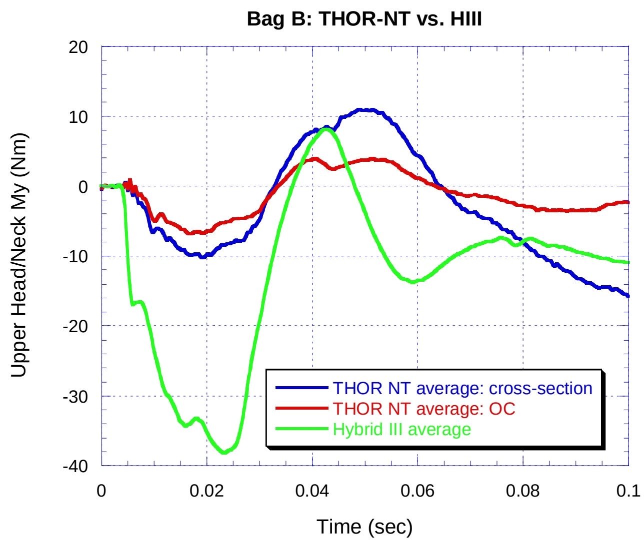
Cited References:

Haffner, M., Eppinger, R., Rangarajan, N., Shams, T., Artis, M., and Deach, D., (2001) "Foundations and Elements of the NHTSA THOR Alpha ATD Design," Paper #458, 17th International Technical Conference on the Enhanced Safety of Vehicles, HS 809 220 (U.S. DOT, 2001).

Chan, P. C. and Lu, Z. (2004) "Laboratory Study of Hybrid-III and THOR Dummy Head/neck Responses to Airbag Load at Close Proximity," SAE Paper 2004-01-0320, 2004.



THOR-NT dummy OOP test setup



Head/neck moment comparison

communications

THORAX FEM VALIDATION AGAINST SEAT BELT TEST

Significance

The human thorax finite element human model was validated against cadaver data obtained from seat belt tests conducted in laboratory.

Product

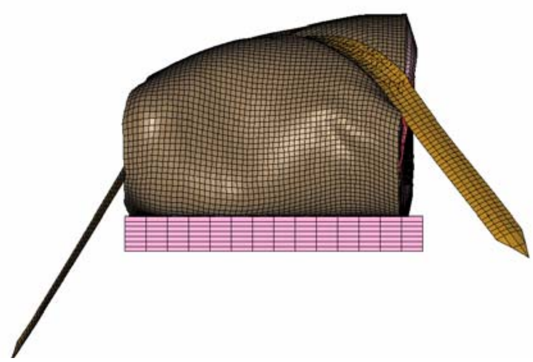
--Finite Element Model Simulation of Seat Belt-Thorax Interaction,Zi Lu and P.C. Chan (2006) Proceedings of the 34th International Work`shop on Human Subjects for Biomechanics Research, Dearborn, MI, 2006.

The seat belt is the most important automobile safety feature today with proven safety record, and it may be possible that the effectiveness of seat belt systems can be further enhanced. On the other hand, given that the driving population is aging and the aging population's tolerance to seat belt loading is greatly reduced, research effort is needed to advance the safety and effectiveness of the seat belt system. Finite element modeling is a needed tool for understanding seat belt interaction with occupant, but such efforts are still very limited due to the difficulties of modeling long-term soft tissue deformation represented in a car crash condition.

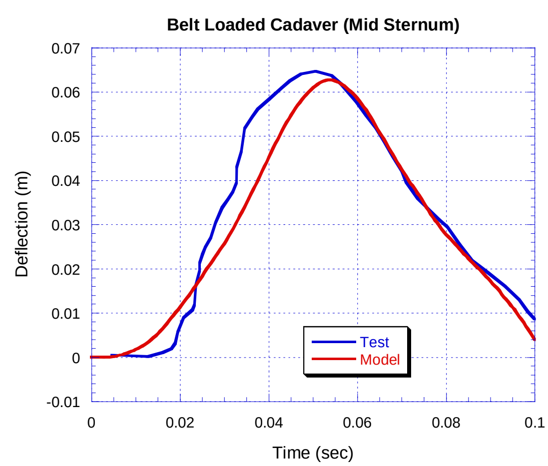
The MRMC human thorax finite element model was used to simulate a laboratory seat belt test using cadaver subjects (Cesari and Bouquet, 1990). In Cesari and Bouquet's tests, a seat belt strap was placed across the torso of a supine cadaver. The two extremities of the belt were routed from the sides of the cadaver down below the table on which it rested, where they were attached to a horizontal rigid bar. The bar was pulled down by an impact device that produced dynamic force. Tension forces in the belt were measured at the two extremities. These forces were used as belt loads in the model to simulate the test. The HyperMesh software was used to fit the seat belts on the thorax similar to the test. The deflection points in the model were monitored at the mid-sternum, lower sternum, right front of the 7th and 9th ribs, respectively. These were the points with deflection-time histories given for cadaver test #17 (Cesari and Bouquet, 1990). The simulated results show good agreement with the data.

Cited References:

Cesari, D., and Bouquet, R. (1990) "Behaviour of human surrogates thorax under belt loading," Proc. 34th Stapp Car Crash Conf., SAE Paper No. 902310.

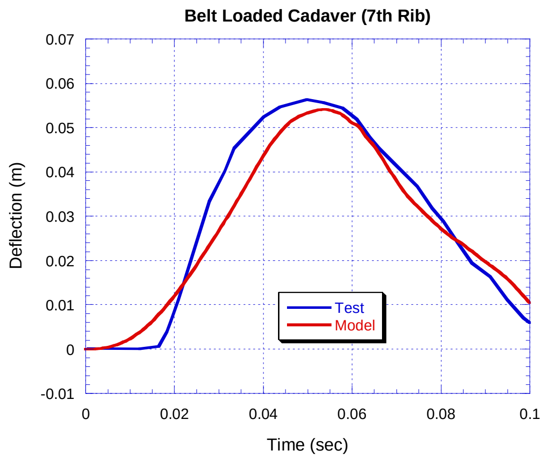


FEM thorax-seat belt model



Mid sternum deflection comparison

communications



7th rib deflection comparison

BLAST DATA PRESERVATION

Significance

Blast injury continues to be a major concern to modern military personnel. Virtually all of the free world's animal testing on blast effects was conducted at the Blast Test Site in Albuquerque, NM from 1950-1995. Those data are preserved at L-3/Jaycor and are being systematically recovered for use in answering current questions.

Product

--Blast Overpressure Database, Ver. 1.0, Diane Long, 2005.

--Kirtland Literature Database, Berlinda Martinez and Brenda Tracy, 2006.

--BOP Data Inventory, Brenda Tracy, 2005.

Research on the biomedical, biological and biophysical effects of blast and shock was conducted at Kirtland Air Force Base, New Mexico from the early 1950's through 1997 (Martinez 1999). The Blast Overpressure Program obtained data that were essential to the understanding of the broad and complex nature of biological effects of blast overpressure and impulse noise.

The primary mission of the research effort was to support programs of national interest by conducting research into the biological effects of exposure to blast overpressures. The experiments performed were designed to address some important military and civilian issues. The results obtained played a major role in the development of blast safety standards, the treatment of blast injuries, development of weapon systems, and tactics to deal with blast overpressure.

L-3 Communications/Jaycor (Jaycor) acquired this data to develop an injury criteria program that will predict injury thresholds to the soldier under different blast conditions. Jaycor was also given the task of documenting the history of this major research effort on the biological effects of blast overpressure and impulse noise and to preserve and archive as many of the documents as possible. The first major task involved inventorying and identifying the materials received from Lovelace, then cataloging, digitizing and organizing the data. so it could be integrated into our current BOP project.

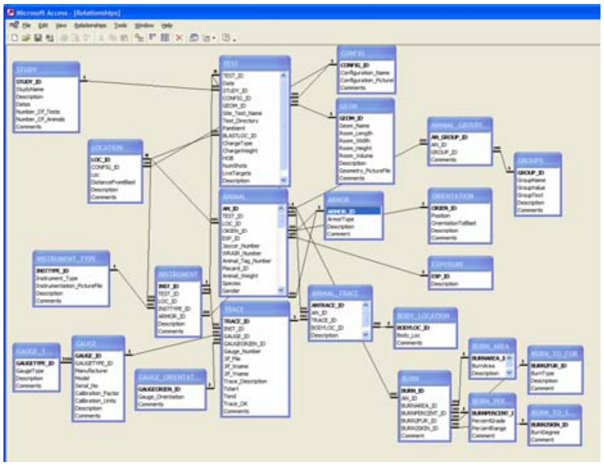
During this contract period Jaycor redigitized all BOP photos that were received previously for higher resolution files with JPG output. We also located and digitized newly found photos and slides and integrated them into the BOP system. Two new studies with behind armor data were identified under the current contract. These were complete studies with pathology sheets, traces, photographs, and logbook pages. All the data was digitized and entered in the database.

Another major effort during this contract period was the development and population of a newly designed database. A quality control was performed to verify that the proper pressure traces were being used by INJURY for each animal. The data was organized into a directory structure that allows INJURY to be run from the QC'd data in the database. A "read only" version of the database was then created and the data is a benchmark for running new correlations for the INJURY software program.

A Kirtland literature database has been created and all the reports have been digitized. The database has links to the PDF versions of the reports and papers and copies of those that are relevant to the different BOP studies have been put in the study folders.

Cited References:

Blast Overpressure Research Program, Kirtland AFB, 1951-1998, Martinez, Berlinda S., Report J2997.74-99-106, Nov. 1999.



Structure and relationships of BOP database

3. Products